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Terrestrial Heat Flow Density in the Zagreb – Karlovac Area

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ABSTRACT

As part of the project „Geothermal map of the Republic of Croatia", initiated in 2007, the broader regions of the cities of Zagreb and Karlovac were investigated (approx. 5500 km^2) in order to determine information on the Terrestrial Heat Flow Density (THFD).The results presented here include computation of THFD at borehole locations and maps of THFD of the investigated area. It has been determined that THFD at the borehole locations varies over a wide range and values differ from those previously published. For most of the studied area, THFD is in accordance with the mean values for continental areas. Two positive (Zagreb and Karlovac) and one negative (Žumberak) geothermal value can be singled out. The map of THFD, as presented here, is different from the previously published maps and is considerably more precise. It is determined that hydrogeothermal sources in the investigated area are not associated with THFD in the above mentioned areas.

Keywords: geothermal map, heat flow density, heat conduction, Croatia

1. INTRODUCTION

In the last twenty years there has been increasing interest in the geothermal potential in Croatia, as this has become an attractive energy resource. Therefore the Croatian Geological Survey (CGS) has been engaged over several years in research activities associated with these issues. Within the project „Geothermal map of the Republic of Croatia", initiated in 2007, the area around the cities of Zagreb and Karlovac has been investigated (approx. 5500 km^2) (Fig. 1) in order to determine the geothermal characteristics. The heat conditions in the depths of our planet, in the Earth crust and the upper mantle in particular, are manifested on the Earth's surface as the Terrestrial Heat Flow Density (THFD). THFD is the amount of heat energy per unit area rising from the Earth's interior towards its surface at a particular spot. Computation of this parameter and its representation on a map is the usual approach to displaying the geothermal characteristics of a particular area. In order to compute THFD at a given location it is necessary to acquire more knowledge on the changes in heat transfer in a conductive regime through the geological formations – geothermal gradient (Γ), depth of formation at particular location, and coefficient of thermal conductivity of individual formations. This information is acquired by measurements, data processing and studying of materials from deep boreholes. Laboratory studies were conducted in the laboratory of the CGS.

Results of THFD computations at the boreholes' locations together with the map of THFD of the investigated area are presented here and compared with previously published data for this area. Published data sources include: the Heat Flow Map of Europe (scale cca 1: 6,000,000) ČERMAK and RYBACH (1979) which displays the territory of Croatia; the Geothermal Atlas of Europe (HURTIG et al., 1992) shows a map of THFD (scale 1:2,500,000), including the territory of Croatia; RAVNIK et al. (1995) presented the Heat Flow Density Map of Slovenia of the area which partially includes the territory of Croatia; the THFD map of Croatia (scale

Figure 1: The Geographic location of the investigated area.

1:4,500,000) published that same year by JELIĆ et al. (1995), while KOVAČIĆ (1995) published his data concerning computations of THFD for locations of several boreholes in the investigated area.

2. METHODS

Methods applied in this research are briefly described separately for the individual geothermal parameters.

Geothermal gradient (Γ)

Temperatures in boreholes are determined by continuous temperature well logging and measuring of „maximum temperature" by maximum thermometer. Data were used from the work of ČUBRIĆ (1993) and from the INA-Naftaplin database. Where the conditions of temperature measurements are known, the temperature values are corrected. Geothermal gradients (Γ) of lithostratigraphic units or their parts were calculated from the static temperatures in certain intervals using the following equation:

$$\Gamma = \frac{T_1 - T_2}{\delta}$$

where T_1–T_2 is the temperature difference between the upper and lower interval limit while δ is the interval thickness in metres.

Thermal conductivity (k)

Thermal conductivity of sediments is determined according to the measurements of the rock samples from the boreholes and, less frequently, of the samples from the same stratigraphic units on the surface. Measurements were carried out by a non-stationary method (Quick Thermal Conductivity Method) (SUMIKAWA & ARAKAWA, 1976; PRELOVŠEK & URAN, 1984) in the laboratory of HGI-CGS. The instruments in use were MTP-4 (VTOZD-Fizika, University of Ljubljana) and ISOMET 2104 (Applied Precision Ltd, Bratislava). According to the manufacturer's data, the measurement accuracy is 10%. It is assumed that the rocks at depths are mostly

Table 1: Data of boreholes (Drilled deposits: Q – Quaternary, Pl – Pliocene, M – Miocene, K – Cretaceous, T – Triassic, Pz – Palaeozoic (uncertain age?); THFD – Terrestrial Heat Flow Density)

Boreholes	Designation on the map	Drilled deposits	Borehole depth (m)	Maximum temperature (°C)	THFD (mWm^{-2})
Dubranec - 3	Dub-3	Q, Pl, M	1603	67	54
Dubravka-1	DKA-1	Q, Pl, M	1090	64	79
Jarun - 1	Jarun - 1	Q, Pl, M	1635	63	61
Karlovac - 2	Ka-2	Q, Pl, M, K, T	4145	152	74
Karlovac - 3	Ka-3	Q, Pl, M, K, T	3523	139	104
Klinička bolnica Novi Zagreb-1b	KBNZ-1b	Q, Pl, M, T	1062	82	106
Komarevo - 1	Kom - 1	Q, Pl, M	917	44	54
Lekenik-1	Lek - 1	Q, Pl, M	1820	78	56
Lomnica - 1	Lom-1	Q, Pl, M, Pz?	1936	95	67
Lučanka-1	Luč - 1	Q, Pl, M	950	58	87
Mladost-1	Mla - 1	Q, Pl, M	1057	77	94
Nedjelja-1	N -1	Q, Pl, M, T	1311	64	75
Odra - 1	Odra - 1	Q, Pl, M	2503	102	55
Podsused-2	PDTE - 2	Q, M, T	530	30	88
Petrinjka - 1	Petrinjka - 1	Q, Pl, M	778	41	59
Popović brdo	Popović brdo	Q, Pl	144	19	52
Precno - 1	Pč - 1	Q, Pl, M, Pz?	3430	122	56
Resnik - 1	Re - 1	Q, Pl, M	1836	76	56
Resnik - 2	Re - 2	Q, Pl, M	1752	83	57
Samobor-2	Sam - 2	Q, M, T	567	25	54
Sava – 1	Sava – 1	Q, Pl, M	1594	84	84
Savica - 1	Sav - 1	Q, Pl, M	2202	94	58
Sisak - 1	Sisak - 1	Q, Pl, M, Pz?	2955	121	68
Stupnik - 1	Stu - 1	Q, Pl, M, T	832	61	96
Sveta Jana - 1	Sv. Jana - 1	Q, Pl, M, T	883	45	47
Šalata termalna-1	ŠalT - 1	Q, Pl, M	1038	52	69
Zelina - 1	Ze - 1	Q, Pl, M	1038	57	67

The THFD map of the investigated area is produced based on the aforementioned calculation (Fig. 2). The THFD data from the territory of Slovenia (RAJVER & RAVNIK, 2002) were taken into account for the purpose of drawing the map.

water saturated. To obtain the thermal characteristics of the samples similar to those of the in situ conditions, the samples were immersed in water for 20 days. According to the previously conducted measurements thermal conductivity is increased by up to 33 % when the porous rocks are saturated (KOVAČIĆ, 2007).

Heat Flow Density

For each interval with a linear increment of temperature (expressed Geothermal gradient – Γ) and defined Thermal conductivity (k) the Interval heat flow density (q_i) is calculated by the Fourier equation (HAENEL et al., 1988):

$$q_i = k\Gamma$$

Terrestrial Heat Flow Density (q_t) is calculated by the interval method (POWELL et al., 1988) from the equation containing the intervals of heat flow density and the interval thickness (δ):

$$q_t = \frac{\sum_{q=1,\,\delta=1}^{n} q_n \delta_n}{\sum_{\delta=1}^{n} \delta_n}$$

or, in a developed form:

$$q_t = \frac{(q_1\delta_1) + (q_2\delta_2) + ...(q_n\delta_n)}{\delta_1 + \delta_2 + ...\delta_n}$$

A map of the Terrestrial Heat Flow Density is made by interpolation using the software package ARCGIS (ESRI).

3. GEOLOGICAL SETTING

The study area is located at the north-western margin of the extensional Pannonian Basin which evolved during the Mio-

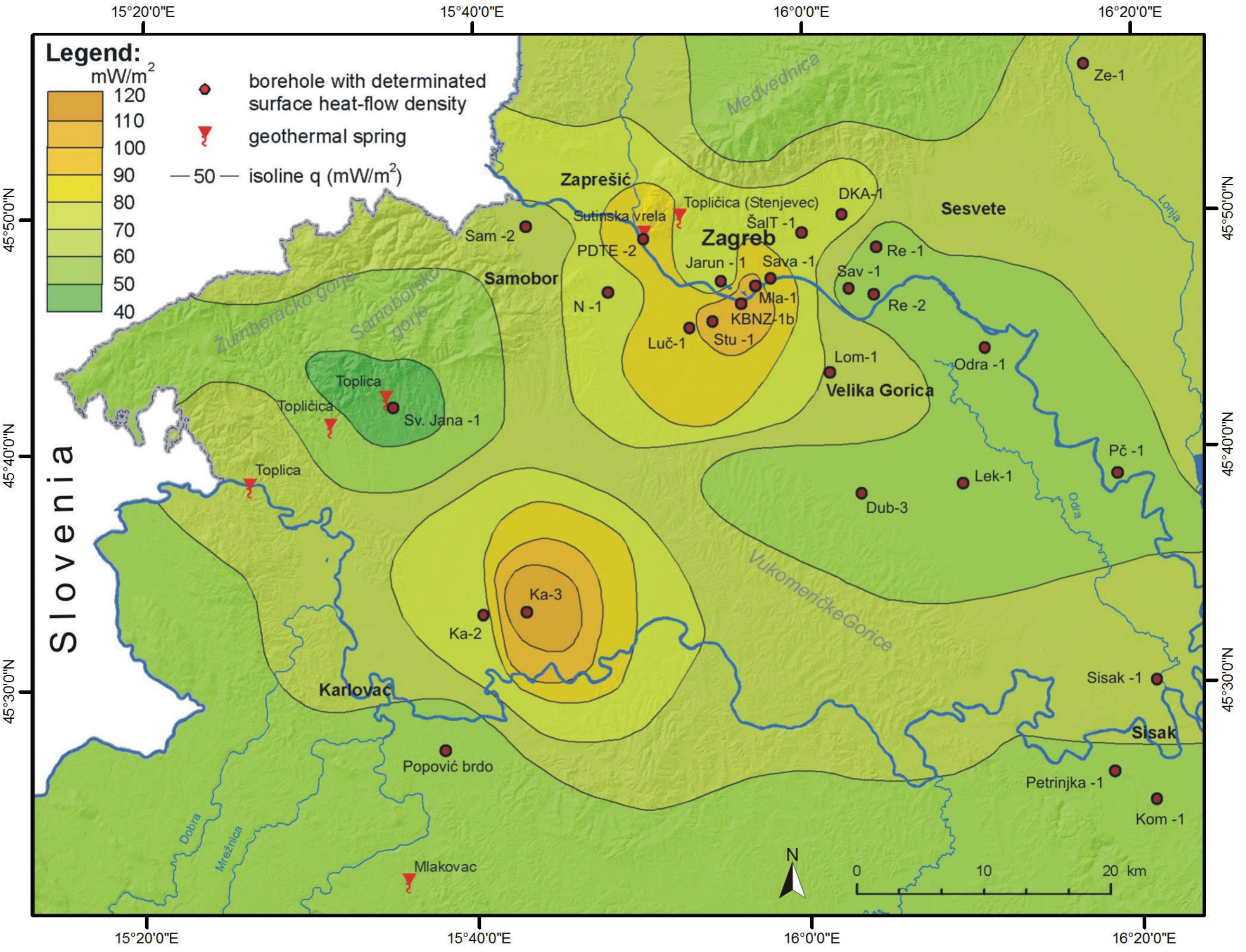

Figure 2: Terrestrial Heat Flow Density map of investigated area.

cene due to continental rifting processes (PAVELIĆ, 2001). The largest part of the terrain is a valley covered by Quaternary deposits, in which the Sava and Kupa Rivers flow (Fig 1). Between the river courses there is a minor hill – Vukomeričke Gorice – with outcrops of Neogene sediments. Mt. Medvednica lies to the North. Geologically, it is represented by a wide range of stratigraphic units dated from the Palaeozoic to the Quaternary. Samoborsko Gorje and the Žumberačko Gorje Mts lie to the NW, where carbonate sediments of the Middle and Upper Triassic age are predominant. These mountains take the form of hills on the west border of the investigated area where Jurassic and Cretaceous sedimentary rocks occur together with Triassic rocks (BASCH, 1980; BUKOVAC et al., 1983; PIKIJA, 1987; PLENIČAR et al., 1976 and ŠIKIĆ et al., 1972).

All boreholes mentioned in this work are located in the lowland part of the investigated area. They drilled through the following successions of sediments: 1. The Pliocene and Quaternary deposits which consist of various types of clastic sediments. The lower, Pliocene part consists of predominantly lime-rich clays with intercalations of coal, sand and marl. In the Quaternary part, the section is represented predominantly by alternations of gravel with sand and clay. The Pliocene section of the deposits is devoid of any significant aquifer, while the Quaternary part is characterized by high primary porosity and permeability, and contains significant quantities of fresh water. 2. Tertiary – a) The Lower and Middle Miocene deposits are represented by the following stratigraphic units: Egerian, Eggenburgian, Ottnangian, Karpatian, Badenian and Sarmatian. Contact with the underlying rocks is unconformable. The lithology varies considerably and consists of marls, sandy marls, sandstone, breccia, breccia-conglomerates and lithothamnion limestone. These beds are characterized by primary and secondary porosity, and occasionally have very good permeability. Also, sporadically they represent reservoirs for thermal water in the investigated area. b) Pannonian - The lower part of this unit consists of marl beds characterized by a high calcite content as well as clayey limestone. These deposits are impermeable. In the upper part, they are composed of marls which are sporadically silty, also impermeable and without primary porosity. c) Pontian – In their lower part these deposits consist of calcareous clays and marls with sporadic intercalations of sandstone. The upper part of these deposits is dominated by calcareous, somewhat sandy clays and marls with rare intercalations of fine-grained sandstone and coal. The deposits are imperme-

Table 2: Comparison of calculated THFD

Boreholes	Designation on the map	THFD mWm^{-2} Ravnik, et al. (1992)	Kovačić (1995)	New calculations
Dubranec-3	Dub-3	67	–	54
Karlovac-2	Ka-2	60 ?	–	74
Karlovac-3	Ka-3	60 ?	–	104
Klinička bolnica Novi Zagreb-1b	KBNZ-1b	–	129	106
Lučanka-1	Luč-1	–	88	87
Mladost-1	Mla-1	–	115	94
Nedjelja-1	N-1	–	68	75
Resnik-1	Re-1	–	58	56
Samobor-2	Sam-2	–	71	54
Sava-1	Sava-1	–	–	84
Stupnik-1	Stu-1	97	119	96

able, characterized by developed primary porosity and with no significant aquifers. 3. Mesozoic – a) low permeability Cretaceous carbonate rocks were drilled only in the boreholes Ka-2 i Ka-3. b) Middle and Upper Triassic dolomite breccia, dolomites, and dolomite limestone, which were determined in the following boreholes: Ka-2, Ka-3, KBNZ-1b, N -1, PDTE – 2, Stu – 1, St. Jana – 1. The rocks are characterized by secondary porosity and high retention of thermal water. 4. Metamorphic impermeable rocks drilled by the boreholes Lom-1, Pč – 1 and Sisak – 1 are thought to be of Palaeozic age (KOVAČIĆ, 2010.)

4. RESULTS

For the calculation of the Thermal conductivity (TC) of the lithostratigraphic units previously published data were used (KOVAČIĆ, 2007). These were updated by the numerous recent data necessary for correction of the TC of the lithostratigraphic units. Measurements were completed on the rock samples from 11 boreholes and on the samples of equivalent stratigraphic units taken from the surface. In total, 1650 measurements on 155 samples were performed. Multiple measurements have been obtained by shifting the sensor and the subsequent statistical analysis has provided the mean TC values of individual samples. These were later used for the computation of the TC of lithostratigraphic units.

Calculation of THFD was performed for the locations of 27 boreholes in the investigated area. The calculation results and the boreholes' attributes are displayed in Table 1.

5. DISCUSSION

THFD is very variable over the borehole locations in the area, ranging between 47 mWm^{-2} (Sveta Jana – 1) and 106 mWm^{-2} (KBNZ-1b) (Table 1). The mean value of THFD is 69.5 mWm^{-2}. Values above the average THFD were determined at 10 locations, and values below average at 17 locations. In the book Heat flow Map of Europe (ČERMAK AND RYBACH, 1979) there is no data on THFD for a single location in the investigated area. This is also the case for the Heat flow density map of Slovenia (RAVNIK et al., 1995). In the Geothermal Atlas of Europe, the THFD data can be observed for 4 boreholes (RAVNIK et al., 1992) (Tab. 2). One of these is excluded from the calculation due to a lack of data. The THFD values for the boreholes Dubranec – 3

Table 3: Global avarage terrestrial heat-flow density (after UYEDA, 1988 and LOWRIE, 1997)

Continental mWm^{-2}	Oceanic mWm^{-2}	Global mWm^{-2}	Total heat output 10^{13} W	Authors
61	61	61	3.11	LEE (1970)
53	62	59	3.01	CHAPMAN & POLLACK (1975)
61	87	77	3.96	LANGSETH & ANDERSON (1979)
53-61	100	81-84	4.15-4.30	DAVIES (1980)
57	99	82	4.2	SCLATER et al. (1980)
65	101	87	4.42	LOWRIE (1997)

Table 4: Springs of geothermal water in the investigated area (classification according to KOVAČIĆ & PERICA, 1998)

Spring	Temperature °C	Classification	Aquifer
Mlakovac	17.5	subthermal	Triassic dolomite?
Sutinska vrela	20.0	sub thermal	Triassic dolomite
Toplica	18.8	sub thermal	?
Toplica (Sveta Jana)	24.1	hypothermal	Triassic dolomite
Topličica (Stenjevec)	17.0	sub thermal	?
Topličica	14.3	sub thermal	?

and Stupnik – 1 differ relatively slightly from the newly calculated data. For the borehole designated as Karlovac the THFD is 60 mWm^{-2}. In so far as the Karlovac-2 borehole is in question the difference between the old and new computed values is relatively small, while for the Karlovac-3 it is high and amounts to 44 mWm^{-2} (Tab. 2). Data acquired by continual temperature logging in Ka-1 and Ka-3 boreholes are indecisive. Here, the most often used data are those obtained by maximum thermometer during the borehole testing, which may explain the variation in computation of the THFD. Since the Atlas is devoid of detailed information on calculations it is impossible to determine the causes for the aforementioned differences in calculation. JELIĆ et al. (1995) do not present data for the THFD of the borehole locations. In the published work, the calculated values of THFD on the borehole locations are mostly somewhat higher than the newly calculated ones (Tab. 2). The varied results are due to different mode of calculation. In KOVAČIĆ (1995) the calculation is made only for sedimentary rocks older than Pliocene and Quaternary ages while the new calculation included all sediments from the bottom of the borehole to the surface. From this, correction of the TC of the stratigraphic unit has been calculated.

Over most of the investigated area the THFD values range from 50 to 70 mWm^{-2} (Fig. 2), and two zones of increased values are clearly visible. One of these is in the southern part of Zagreb extending northwest towards Slovenia. Here the THFD ranges from 70 to 106 mWm^{-2}. Another one, with THFD values ranging from 70 to 104 mWm^{-2} extends to the area northeast of Karlovac. The THFD value and the extension of this zone are questionable due to both the aforementioned inconclusive data concerning the temperatures measured in Ka-1 and Ka-3 boreholes and the fact that only two boreholes exist in this area. In the area of Samobor and the Žumberak Mts. there is a zone with THFD less than 50 mWm^{-2}. When compared with data from all over the world, the THFD values from most of the investigated area show the average values for the continents (UYEDA, 1988) (Tab. 3). Due to the close relations of the THFD in the investigated and surrounding areas (HURTIG et al., 1992; RAJVER & RAVNIK, 2002), the zones of the increased THFD can be called the Zagreb and Karlovac positive geothermal anomaly. By the same token, the area with the smallest THFD can be called the Žumberak negative anomaly. Because both the Karlovac and Žumberak geothermal anomalies occupy relatively small areas we can call them local while the Zagreb anomaly which extends towards Slovenia (Krško) can be defined as regional.

Comparison with hitherto published maps of the THFD comprising the investigated area is difficult because the latter are, represented on a much greater scale. On the Heat flow Map of Europe (ČERMAK & RYBACH, 1979) THFD in the investigated area ranges between 60 and 70 mWm^{-2}. On another map of THFD by HURTIG et al., (1992) the values range between 50 and 80 mWm^{-2}. On the Heat Flow Density Map of Slovenia (RAVNIK et al., 1995) the THFD values are in 40– 80 mWm^{-2} range, whereas on the one by JELIĆ et al. (1995) they fall in the 50 – 85 mWm^{-2} range. On both maps the highest values of THFD are in the area of Zagreb, while in the area of Karlovac the THFD is considerably lower with regard to the value determined by this research.

In the investigated area there are 6 springs of geothermal water (Fig. 2, Tab. 4). The water temperature at the springs is relatively low, being higher with regard to mean annual temperature characteristic of the spring areas by only 4 to 14 ^{0}C. Two springs are located in the area of the Zagreb positive anomaly and two in the area of the Žumberak negative anomaly. Therefore it can be concluded that the spring locations and THFD are not related at these locations.

6. CONCLUSIONS

THFD in the boreholes in the wider area of the cities of Zagreb and Karlovac (cca 5500 km^2) is very variable ranging between 47 and 106 mWm^{-2}.

Over most of the investigated area THFD ranges between 50 and 70 mWm^{-2} which is in accordance with the average values for the continental areas.

Two positive (Zagreb and Karlovac) geothermal anomalies and a single negative (Žumberak) geothermal anomaly depart from the above values. According to their magnitude it can be said that the Karlovac and Žumberak anomalies are local whereas the Zagreb anomaly is regional as it extends toward the Slovenian territory.

Based on the magnitudes and spatial distribution of THFD in the investigated area it can be concluded that a considerable geothermal potential exists in the zone of the positive Zagreb and Karlovac geothermal anomalies.

The map of THFD as represented here differs with regard to maps hitherto published and is considerably more precise due to the scale and much greater number of points used in calculation.

The location and temperature of water in six geothermal springs in the investigated area are not associated with THFD in that area.

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